The Structure and the Characteristics of the Electromagnetic Field Generated by a High-Power Radio Electronic System

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***Abstract*—A high-power radio electronic system represents an important source for electromagnetic disturbances within the specific electromagnetic framework of a region or a country. The large diversity of the radio electronic systems includes many military high-power systems and among them, the Ground Based Air Defense (GBAD) systems. In order to assure an electromagnetic compatibility environment (EMC), a highly professional assessment must be performed, to determine the electromagnetic disturbing potential of a system. This article provides a synthetic analysis of the electromagnetic field generated by a GBAD system, from its structure and characteristics point of view, starting with the specific electromagnetic disturbing processes existing at each subsystem and ending with a review of a main electromagnetic disturbances produced and its potential "victims". Moreover, the article shows the scientific connection between the particular functional processes at the subsystem level and the appearance of the electromagnetic disturbances, fact very rarely explained in public sources.**

***Index Terms*—EMC, GBAD, electromagnetic disturbances, electromagnetic disturbing potential, array factor.**

I. Introduction

The air defense of a country represents one of the essential security objectives of that state. Due to the evident scientific research progresses in the field of cruise missiles and unmanned aerial vehicles (UAVs), these became a major threat and a priority in establishing the fight engagement rules, in order to defeat and destroy them at as far as possible distances from the defended objective.

Under these circumstances, the role of GBAD systems remains an extremely important one, the modern armies being constantly engaged in the upgrading race and purchasing new versions of these weapon systems to permanently meet the new challenges of the modern war.

In the same time, the use of a GBAD system, both in training process and during the war time, leads in the appearance of important disturbing electromagnetic processes which affect the functionality of the other military or civilian equipment and are determining factors for the analyses performed with the purpose to assure the electromagnetic compatibility.

The EMC assurance between the military systems of an army and also the EMC assurance between them and miscellaneous civilian radio electronic systems, represents not only a goal, but a constraint imposed by laws, regulations and standards whose respecting is carefully guarded by the national and international especial dedicated authorities.

The scientific instruments dedicated to assess the disturbing profile of a GBAD system are very rare, both in public sources and technical documentations issued by the producers of this weapon system, most of them being limited to test the equipment belonging to the system and assessing the way in which they meet the constraints imposed by the applicable EMC standards. Moreover, the verification results are limited to the subsystem level and no complex verifications at the system level being made.

This type of information is not provided even to the system buyer, most of the time, the information related to the electromagnetic disturbing potential of the system being restrained to the issuance of EMC certificate to testify the fact that specific equipment meets the limits imposed by the MIL-STD-461 G Standard.

In order to obtain such extremely important data for the success of the military operations, a "real" testing process has to be performed, which is very costly and complex. During such process, are verified one by one, from EMC point of view, the "pairs" composed by a GBAD system and another military radio electronic system.

The analysis of the existing specialty literature also emphasizes the absence of the in-depth scientific presentations of the connection between the GBAD component's functionality and the appearance of the electromagnetic disturbances issued by them. That is why, this article describes more consistently this connection, and contributes to the completion of the problematic context related to the GBAD systems specific electromagnetic disturbing processes.

II. The Electromagnetic Disturbing Phenomena and the Applicable Official Framework

In Romania, the Government Decision no. 487/2016, on electromagnetic compatibility represents the official reference within the EMC field of activity. It implements the Directive 2014/30/EU (EMC Directive) of the European Parliament and of the Council, as of 26 February 2014, on the harmonization of the laws of the Member States relating to electromagnetic compatibility, having the aim to harmonize the rules governing the sale within the EU of equipment liable to generate electromagnetic disturbance or to be affected by it.

At the article no. 2, para (1), point 18, a meaning of the *harmful interference* [1] is presented: "any electromagnetic phenomenon which may degrade the performance of equipment, such as, but not limited to electromagnetic

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noise, to an unwanted signal or a change in the propagation medium itself".

The effect of an electromagnetic disturbance consists in the energy transfer to the victim.

The electromagnetic phenomena have been classified by the International Electrotechnical Commission (IEC) in six categories [2], as follows:

1. Conducted low-frequency phenomena:
   - Harmonics, interharmonics;
   - Signalling systems;
   - Voltage fluctuations;
   - Voltage dips and interruptions;
   - Voltage unbalance;
   - Power frequency variations;
   - Induced low-frequency voltages;
   - DC in AC networks;
2. Radiated low-frequency field phenomena:
   - Magnetic fields:
     - o continuous;
     - o transient;
   - Electric field;
3. Conducted high-frequency field phenomena:
   - Directly coupled or induced voltages or currents:
     a. continuous wave;
     b. modulated waves;
   - Unidirectional transients*****;
   - Oscillatory transients*****;

     * Single or repetitive (bursts);
4. Radiated high-frequency field phenomena:
   - Magnetic fields;
   - Electric fields;
   - Electromagnetic fields;
     a. continuous wave;
     b. modulated waves;
     c. transients;
5. Electrostatic discharge phenomena (ESD);
6. High-altitude nuclear electromagnetic pulse (HEMP).

Regarding the conducted low-frequency disturbances, an eloquent representation is offered by the IEEE 1159-2019 Standard, published on August, 13rd, 2019. Within this standard, a similar to the above-mentioned definition of the electromagnetic disturbance (interference) is presented: "any electromagnetic phenomenon that can degrade the performance of a device, equipment, or system, or can adversely affect the living or inert matter".

Coming back to the GBAD systems, first four of the above-mentioned categories of electromagnetic phenomena are applicable to these types of radio electronic systems.

III. GBAD System as a Source of the EM Disturbances

Usually, a GBAD system unit cell is organized as a battery and includes the following components:

1. A radar subsystem;
2. An engagement control station;
3. The interceptors (ground-to-air missiles) launching stations;
4. The interceptors;
5. A communication subsystem;
6. An electric power generating subsystem.

Each of the above-mentioned subsystems includes electric and electronic equipment which represent true sources for electromagnetic disturbances.

The particularities of the subsystems belonging to a GBAD system, from the point of view of its behavior as electromagnetic disturbances sources, will be presented in the following, in ascending order of its disturbing potential.

The power generating subsystem has the role to generate the electric power used for the functioning of the radar subsystem, the engagement control station, the communication subsystem and also, from case to case, for the launching stations functioning (usually, these subsystems have their own power generators). Usually, the power generating subsystem consists of two generators sets (diesel engine - synchronous generator), each of them having the capacity to produce up to $150\,kW$ power and $200 / 120\,V / 400\,Hz$ three phased voltage. Also, the power generating subsystem includes an electric power converter which is used when the GBAD system uses the electric energy from the domestic power grid voltage $220\,V / 50–60\,Hz$, three phased), to converse the level and the frequency of this electric power in $200\,V / 400\,Hz$ voltage needed for the GBAD equipment functionality.

The operating principle of a synchronous generator is very known; it consists in producing the electricity through electromagnetic induction phenomenon. This is possible, either through rotating a metallic coil within a magnetic field, either through rotating the magnetic field in relation with a metallic coil. In the synchronous generator case, the second option is applied, as will be described in the following.

A synchronous generator (also known as "alternator") is composed by two main parts: a mobile one named rotor and a fixed one named stator (Fig. 1).

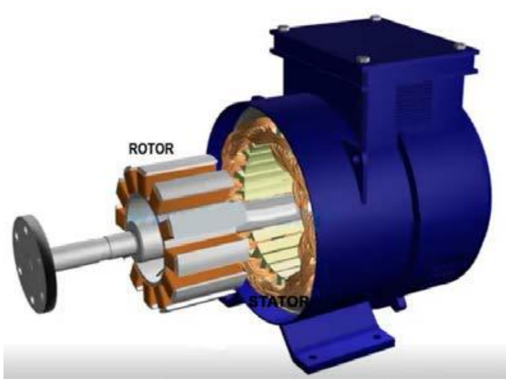

Figure 1. The alternator

The rotor is composed by a metallic shaft on which the poles (polar pieces) are mounted. The poles have a ferromagnetic ($\mu >> \mu_0$) core built of insulated metallic sheeets (in order to reduce the energy loss due to the eddy currents, or Foucault currents). On these mettalic sheets, a rotoric winding is disposed to form the rotor coils which are excited by a continuous current source to produce a magnetic field.

The rotor is coupled with the termic engine's shaft and it spins together with this one, rotating in this way, also the magnetic field produced by its coils.

The calculation relationship of the 1st harmonic (the fundamental) of the magnetic induction at the level of the air

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gap (the space between the rotor and the stator) is [3]:

$$B_1 = B_{1m}\cos\left(pa - w_1 t\right);\ B_{1m} = \left(\mu_0 N_1 K_f I_1\right)\Big/ d\,, \qquad (1)$$

where B_{1m} is the maximum amplitude of the fundamental, p is the number of poles pairs, α is the angle between the vector radius which passes through the reference point in air gap and the axis of a North pole, $\omega_1 = p\Omega_1$ is the pulsation of the rotating field (Ω_1 being the angular velocity of the rotor), K_f is the shape coefficient (the ratio between the effective value of the magnetic induction – $B_{\max}\big/\sqrt{2}$ and its average value), and δ is the average size of the air gap (space between rotor and stator, in mm).

The rotation of this magnetic field leads to the variation of the inductive magnetic field in relation with the stator's coils and, according to Faraday's electromagnetic induction law, this variation has as an effect, the production of an induced electromotive voltage within these coils. The frequency of this voltage is directly proportional with the diesel engine's speed and with the number of its poles. We used the plural when speaking about the stator's coils, because it's a matter of three coils disposed symmetric at 120° one from another. The values of the induced electromotive voltages and also those of the currents throughout the stator's coils are related to the charge's type (active or inductive).

The symmetrical three-phase current system will in turn produce a spinning magnetic field of reaction.

The two rotating magnetic fields (inductor and reaction) rotate synchronously, having the same pulsation and the same rotation speed. They compose and form the resulting magnetic field which forms with the direction of the inductive magnetic field an angle θ also called the internal angle of the synchronous machine.

Considering Faraday's law of electromagnetic induction, the variation of the resulting magnetic field leads to the formation of an associated electric field, so that we can speak of an electromagnetic field that is in fact a radiated disturbance. In order to limit the propagation of this disturbance, the entire rotor-stator assembly of the alternator is inserted into a closed metal housing at the ends of two shields. It not only has the role of protecting the two subassemblies and limiting the direct access of people or soundproofing, but especially has the role of electromagnetic shielding.

The above brief description of the operation of the synchronous generator allows us to review the disturbing electromagnetic processes that can occur in the generator set, as follows:

a) fluctuations in the level or frequency of the three-phase voltage generated, caused by the malfunction of the heat engine (accidental, short-term change in its speed, due to impurities that may cause interruptions in the fuel supply circuit or due to improper quality of fuel); changing the speed of the heat engine leads to changing the speed of the alternator rotor, so to change the excitation voltage (in the case of self-excited synchronous generators, where the exciter is mounted on the same shaft as the rotor) whose effect is to change the amplitude of the inductive magnetic field and finally the change in the level of electromotive voltages induced in the stator windings, but also in their frequency which is directly proportional to the rotational speed of the rotor; to prevent / correct this type of phenomenon, synchronous generators have automatic voltage regulators (Automatic Voltage Regulator - AVR);

b) the electric arcs (sparks) produced at the level of the collector brushes of the exciter (the direct current generator that creates the excitation voltage of the rotor winding); the collector brushes provide the electrical connection between the moving part of the direct current generator (the collector) and its fixed part (Fig. 2). The brushes are made of pressed coal dust, pressed graphite or pressed copper dust and are mounted in metal boxes called brush holders. The passage of the brush from one blade to another of the collector should be done when the voltages in the windings connected to these blades are minimal (they are at that time on the neutral geometric axis), but due to the angular gap that the resulting magnetic field it does it with the neutral geometric axis, in the respective windings there are significant tensions that lead to the appearance of sparks between the lamella and the brush due to the self-induction phenomenon.

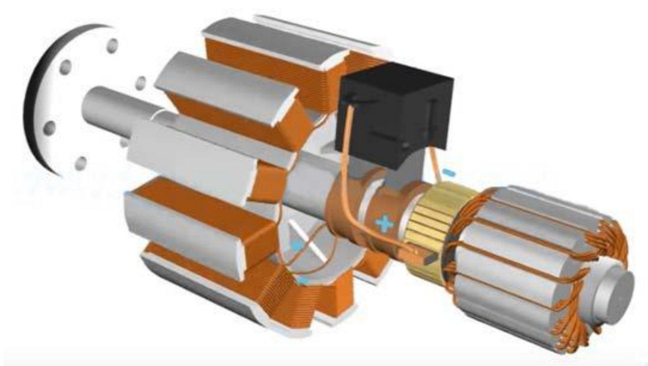

Figure 2. Rotor-exciter assembly

The sparks produced represent an electromagnetic noise that affects the quality of the three-phase voltage generated by the alternator, but also a source of low frequency disturbances (harmonics with the frequency up to 200 *kHz*);

c) electric arcs (sparks) produced at the level of control / switching elements (contactors, relays, etc.) in the electricity distribution unit of the generator set. These transient rapid variations have a very wide spectrum, generally occur at the switching of inductive loads and are manifested by voltage pulses (peaks) lasting between 0.1 and 10 µs which have the strongest effect when centered on the tip of the sinusoids. voltage. Theoretically, the amplitude of such pulses reaches values of tens of *kV*, but in reality, when the potential difference between the contacts reaches the value of 3.7 *kV* (at atmospheric pressure of 1 atm), an electric arc is produced which restores for a short time the current through the circuit, until the electric arc goes out;

d) harmonic distortions of phase voltage and current; harmonics are defined as voltages or currents whose frequencies are an integer multiple of the fundamental frequency. For the 400 *Hz* three-phase voltage signal generated by the synchronous generator, the harmonic whose frequency is 1200 *Hz* (1.2 *kHz*) is known as the 3rd harmonic. The third order harmonics are defined as the odd multiple order harmonics of the 3rd order harmonics (3rd, 9th, 15th, 21st, etc.), these being homopolar succession harmonics, as opposed to the fundamental one, which is of direct succession. The consequence of this characteristic aspect is that, in three-phase systems provided with a neutral conductor, the amplitudes of the harmonic currents in the phases add up in the neutral conductor, even if the respective currents form a symmetrical system. This can sometimes lead to very high currents in the neutral conductor (120–130% of the current value per phase), and if it is not properly sized it can overheat, and the risk of fire may occur. By star coupling the stator windings, this effect is removed. However, the effects produced by the other odd harmonics remain (5^{th}, 7^{th}, 11^{th}, etc.);

e) the maximum magnetic flux at the nominal load can be a disturbing factor;

f) the even harmonics and the subharmonics determined by the operation of the converter. At the level of the ‘60s and ‘90s, the asynchronous rotary converter was used in the ground-to-air missile system. This was an electrical device consisting of a three-phase asynchronous motor with a short-circuited rotor, with a drive role and a frequency generator which was also a three-phase asynchronous motor. Both the drive motor and the frequency generator had stator windings supplied with a frequency voltage $f_1 = 50\ Hz$ from the three-phase industrial voltage network (3 × 220 *V*, 50–60 *Hz*). The rotor of the drive motor was coupled to the frequency generating rotor on whose collector rings the increased frequency $f_2 = 400\ Hz$ was obtained. This was related to the frequency f_1 of the supply voltage of the generator stator and to the sliding “*s*” of the generator through the relation $f_2 = s \cdot f_1$. For the frequency f_2 to be higher than the frequency f_1, the slip *s* had to be greater than 1 (in the case of the frequency of 400 *Hz*, $s = 8$). For this purpose, the frequency generating rotor was rotated by the motor rotor in the opposite direction to the rotating magnetic field of the stator with a rotational speed $\Omega = \Omega_1 \cdot (s-1)$, Ω_1 being the rotational speed of the rotating magnetic field. This type of converter needs a rigorous and substantial periodic maintenance, presenting all the shortcomings shown above to the synchronous electric generator.

The latest generation GBAD systems use industrial static converters (cycloconverters) made using “solid-state” technology, with semiconductor power elements (diodes, thyristors, etc.). In general, the principle of frequency conversion is based on the deformation of the sinusoidal voltage of the source and the appearance of its higher harmonics.

The harmonic analysis of the output voltage of a cycloconverter, treated in the specialized literature [4], highlights the existence, besides the pulsation fundamental ω_0, of two families of superior harmonics, of pulsations $\omega_{n1} = 3(2k-1)\omega + 2k'\omega_0$ and $\omega_{n2} = 6k\omega + (2k'-1)\omega_0$, where $k \in \mathbb{N}^*$ and $k' \in \mathbb{N}$. When the converter is coupled to the load, these voltage harmonics lead to the creation of harmonic currents by the load impedance and therefore, there are changes in the level of the useful voltage that supplies the load. This affects electrical equipment through dielectric and thermal overloads on capacitors and motors.

The operation of the launching station’s electric motors is the cause of intermittent broadband electromagnetic disturbances. When separating the brushes from the edges of the collector blades, the current is not zero but is maintained by an electric arc. When this arc is interrupted, there is a rapid current variation that induces a self-induction voltage in the winding (inductance) whose ends are connected to the slats on which the brushes are currently treading, as well as mutual induction voltages in neighboring windings. The transient processes in electric motors lead to the appearance outside their housing of a magnetic induction of up to 450 μT, corresponding to the dispersive magnetic field.

The operation of the existing control elements (relays, switches) at the level of the launchers is the cause of transient broadband disturbances. Switching inductors (relay and contactor windings) gives rise to high value transient overvoltages (of the order of *kV*) which, in addition to deteriorating the winding insulation over time, electromagnetically disrupt the electronic components and circuits arranged near them.

The engagement control station is located at the level of an operational control center arranged in a mobile container and contains a central data processing unit (radar subsystem status, target position, flight parameters, launch preparation stage of launchers and interceptors, etc.) and equipment necessary for operators to visualize the area covered by the radar subsystem, to view targets and track their trajectories, to visualize the trajectories of missiles launched to the target, and to ensure communications with the radar subsystem, missile launchers, neighboring fire units and battalion command.

The container in which the operational launch control subsystem is located includes equipment that allows its use in NBC and EMP contaminated environments, being protected against electromagnetic disturbances. Therefore, the potential internal sources of electromagnetic disturbances, represented by the operation of the electrical and electronic equipment arranged in the container are important only for the environment inside it. The influence of the existing communication terminals in the container of the operational launch control subsystem is to be analyzed within the communications subsystem.

From the point of view of the sources of electromagnetic disturbances, at the level of the launch operational control subsystem, two potential sources are important, namely the tactile pulse generator necessary for the operation of the central data processing unit (central computer) and the indicating devices, through the voltage generators.

Due to the multitude of instructions, addressing modes, and operations it must perform (which can reach up to 8 million per second), the central processor unit is a military product organized as a multiprocessing unit that operates at a clock frequency of tens of thousands *MHz* (25 *MHz*, for the PATRIOT system). Given the need to perform as many operations per second, it is necessary that the working speed of a processor is as high as possible, so the clock frequency is as high as possible. However, a high frequency of the clock signal creates the disadvantage of emitting electromagnetic disturbances through the connecting conductors between the clock generator and the controlled circuits. For example, at a frequency of 100 *MHz*, a conductor with a length of 1 *m* has the properties of a radiant dipole that can transmit

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electromagnetic disturbances that can affect the operation of integrated circuits in its vicinity.

The use of high-speed, miniaturized digital devices and systems, as well as their 'crowding' in small spaces, has led to the need to establish rules and constraints on their design and manufacture.

In the United States, the Federal Communications Commission (FCC) has imposed limits on radiated emissions and controlled emissions from wireless and radio communications processes. Part 15 of the FCC Rules and Regulation [5] sets out the technical standards and operational requirements for radio frequency devices. Chapter J of Part 15 sets out the rules applicable to digital electronic devices, which are divided into two classes. Class A includes digital devices intended for commercial, industrial or business use, and class B includes digital products for residential use.

In Fig. 3 are shown the limits for emissions radiated by a calculation system, these being measured at a distance of 3 m of product.

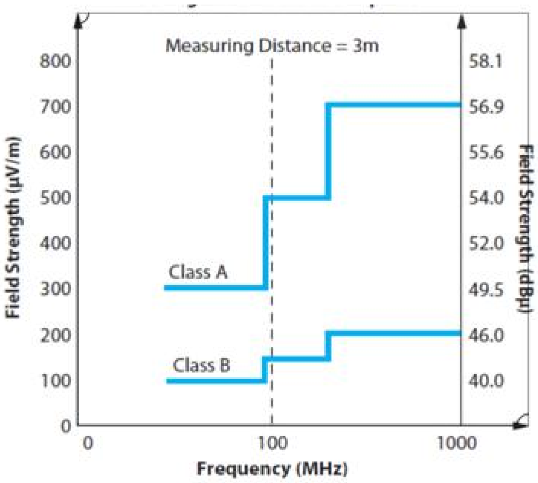

Figure 3. FCC Regulation on the Radiated Emission for Computing Device

It is noted that the maximum permissible level of disturbances emitted by a computing system operating at a frequency of up to 100 MHz is $300\ \mu V/m$ ($49.5\ dB\mu V/m$).

In the field of military equipment, the limits of the disturbances emitted by them are set out in the MIL-STD-461G Standard. Taking as an example the provisions of this standard regarding the emission limits of equipment related to systems used in terrestrial applications, RE102 (Fig. 4), it is observed that these limits are more restrictive than the limits imposed by the FCC on "civilian" equipment, respectively $24\ dB\mu V/m$ ($158\ \mu V/m$) for operating frequencies between 100 *kHz* and 100 *MHz*.

The maximum levels of interference emitted by existing equipment in the engagement control station of a GBAD system manufactured according to a recent technology are much lower than those of electronic tube equipment that equipped GBAD systems manufactured in the '70s. The protection of the operators within this subsystem against the electromagnetic fields emitted inside the station is currently achieved by implementing, from the manufacturing phase of the components, the rules imposed by EMC standards, without the need to ensure the physical protection of people, as in the past, by equipping them with protective devices (lead aprons).

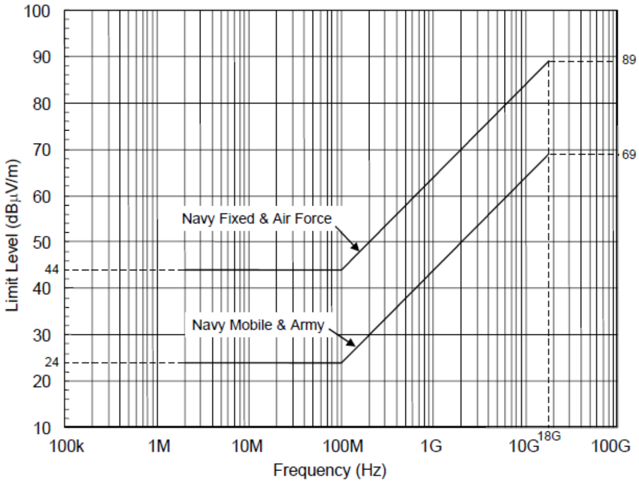

Figure 4. Radiated emissions limits for ground applications [6]

Ground-to-air missiles (interceptors) are intended to combat and destroy air targets entering in the destruction zone of the GBAD system. They are launched from launch stations (launch ramps / launchers) and carry a combat payload to the target that explodes either near the target (using a proximity warhead) or explodes on impact with the target (according to the principle of "hit-to-kill" or "body-to-body impact"). By using the engagement control station, the interceptors are directed, with the help of radio commands, towards the target on an optimal trajectory, so as to ensure a high probability of destroying the target. Also, in order to increase the probability of destruction, the latest generation GBAD systems use the "track-via-missile" (TVM) principle, meaning that the radar subsystem uses in addition to information about the position and speed of the target obtained by reflecting the waves emitted in space by the radar, target information provided by the ground-to-air missile, which can obtain them either in "semi-active" mode, by processing and transmitting to the radar the target information obtained from radar waves reflected by the body target, either in "active" mode, in which case the missile includes a "seeker" consisting of its own radar subsystem with which "illuminates" the target. For example, the PAC-3 missile, related to the GBAD PATRIOT system, contains a seeker working in the Ka band (representing the frequency range 27 – 40 *GHz*).

The electromagnetic disturbance potential of the ground-to-air missile is represented by the following characteristic signals:

- the signals transmitted on the data links between the ground radar and the missile, channel on which the missile command / control commands are transmitted on the initial flight portion (until the "catcher" of the target by the seeker) and the target data obtained by the missile; in the GBAD PATRIOT system they have the carrier frequency in the C band (4–8 *GHz*);
- the "sounding" signal emitted by the seeker;
- the signals resulting from the interaction of the electromagnetic waves emitted by the missile or existing in the environment of the ground-to-air rocket with the plasma jet resulting from the combustion of the missile's solid fuel engine; this interaction consists in the appearance of the phenomena of reflection, refraction, diffraction, absorption and change of the phase of electromagnetic waves.

The communications subsystem ensures the data and voice links between the subsystems of a GBAD fire unit (battery), between it and the upper echelon (battalion command) as well as between the battery and independent control and warning systems (such as for example the AWACS System – Airborne Warning and Control System) and even with satellite communication systems.

At the level of a ground-to-air missile battalion, communications can be ensured by using up to three independent radio systems. The first radio system uses equipment that works in the UHF band and provides voice and data links between the engagement control station in the fire battery composition and the information and coordination center at the upper echelon (battalion), the latter representing the point of entry and battalion-level exit for all target engagement operations. The second radio system uses equipment that works in the VHF band and provides tactical voice communications between the fire batteries of a battalion and between each of them and the battalion command. The third radio system is intended to provide data links between the components of a fire battery and uses frequency hopping transceivers that also work in the band VHF. This radio system is "doubled" by connections through fiber optic channels.

It is well known that both ultrashort waves (from the VHF band) and decimetric waves (from the UHF band) propagate through the direct wave and the space wave reflected by the troposphere, ensuring a stable radio link within the line of sight (Line of Sight – LOS). Therefore, in the situation where the terrain configuration offers a short distance to the limit of direct visibility, GBAD systems use radio relay stations and mobile retranslation equipment with telescopic antennas, to extend radio links to the maximum distance required by the functional performance of equipment. An example of a radio relay station used in the communications subsystem of a GBAD system is AN / GRC-245 produced by the Canadian company Ultra Electronics TCS. It operates on frequencies between 1350 and 2690 *MHz*, automatically and continuously tuning the operating frequency within this range at a rate of 125 *kHz*. This equipment is capable of providing a stable communications link over a distance of up to 40 *km* [7].

The signals emitted by this radio relay may constitute electromagnetic disturbances for other radio systems located within a radius of 40 km around it, starting from fixed lines of low capacity (in the band 1350–1375 *MHz*), continuing with the military aeronautical, maritime and terrestrial systems which have assigned the frequency band 1362.50–1400.00 *MHz* and up to terrestrial systems capable of providing electronic communications services (MFCN Networks – Mobile / Fixed Communications Networks, with the working band 2670 – 2690 *MHz*).

The radar subsystem is the main source of electromagnetic disturbances for other radio / electronic systems / equipment. New generation radars use rapid electronic steering of beams, which are very narrow (1–2° HPBW) in both planes ("pencil" or beam type), which are steered electronically over the entire area of the sector to be observed, speed thus decreasing from the order of seconds to that of microseconds. Electronic beam steering can be performed according to a certain program that can be adjusted so that certain targets or parts of the observation sector are observed more often. In this respect, GBAD radars use phased arrays of antennas consisting of a number of elementary antennas (dipole, chimney, slot antennas, special antenna elements, etc.) arranged in the same plane, in rows and columns, at equal distances (from rule $\lambda/2$). Behind these elementary antennas a reflector is placed, so that all the energy is radiated in one direction.

The radiation pattern of a phased-antenna array is obtained by combining in space the radiation pattern of each elementary antenna, based on the interference phenomenon of electromagnetic waves, the resulting pattern being narrower and "stronger" ("longer"). Better directivity leads to an increase in gain, and a higher gain leads to a decrease in the level of power that must be issued to obtain the same power at reception. For example, a 10-fold increase in the gain of an antenna allows the power of the transmitter to be 10 times lower to obtain the same signal at the input to the receiving antenna.

The electronic shift of the beam is achieved by introducing a constant phase shift from one elementary antenna to another, a phase shift that introduces a delay of the signal radiated into space by it, so that the resulting wavefront of the entire array will be tilted compared to the normal direction at its surface. It should be noted that as the beam inclination angle increases, the antenna gain decreases and the beam width increases. Because of this, the radar observation sector that uses electronic scanning is usually limited (for instance, 120°).

In the case of the antenna array, the principle of "multiplication" of the radiation pattern is used to calculate the resulting electric field, which says that the directivity function of a phased-antenna array $F(\beta,\varepsilon)$ (where β is the azimuthal angle and ε is the elevation angle) consists of the product between the directivity function $F_e(\beta,\varepsilon)$ of an antenna element and the Array Factor $AF(\beta,\varepsilon)$, which depends on the displacement of the elementary antennas in the array, the aperture shape of the array, the number of antenna elements and the amplitude of their excitation / the weighting level of the field captured by each element of the array. This principle is based on the hypothesis that all antenna elements in the array have identical radiation patterns, and at sufficiently large distances from the area, they are parallel.

In reality, however, due to the mutual coupling between the antenna elements, the current distribution on them differs from one antenna element to another, so that the antennas in the center of the array are influenced differently from those at its edge.

The half wavelength dipole is the most used elementary antenna in antenna arrays.

The radiation pattern of the $\lambda/2$ dipole is omnidirectional on the perpendicular plane to the dipole axis and the HPBW in the plane containing the dipole axis is roughly 78 degrees when the array has a reflector (Fig. 5a and Fig. 5b).

Considering the dipole horizontal placed, its directivity function is zero along the dipole's axis and maximum in the direction perpendicular to it, according to the relation [8]:

$$F_e(\beta,\varepsilon) = \cos\left[(\pi/2)\cdot\cos(\beta)\right]/\sin(\beta). \quad (2)$$

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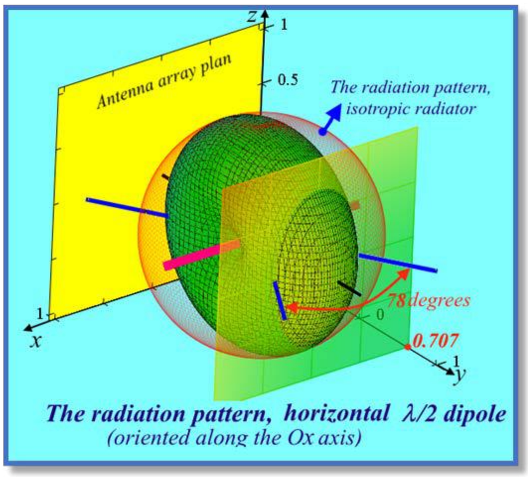
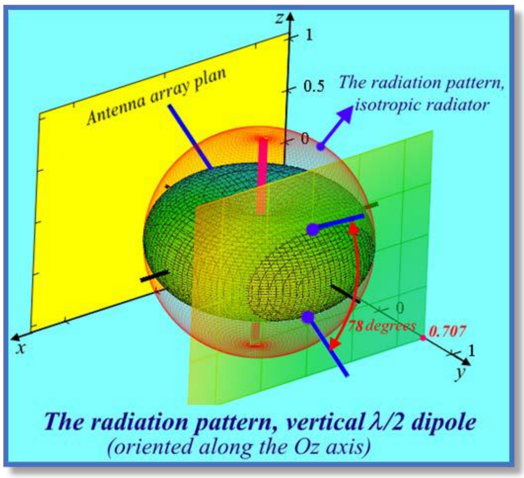
Consequently, the dipole radiation pattern does not influence the directivity of the arrays with higher number of the elements, but only the array factor AF does.



a)



b)

Figure 5. a) The horizontal dipole radiation pattern; b) The vertical dipole radiation pattern

In Fig. 6, an example of 3D graphical representation is presented regarding the array factor of a phased-antenna array consisting of 100 half wave horizontal dipoles (10 lines × 10 columns – square aperture), evenly distributed (the distance between rows d_r and the distance between columns d_c are $\lambda/2$) and uniformly excited. The mutual coupling between dipoles is ignored.

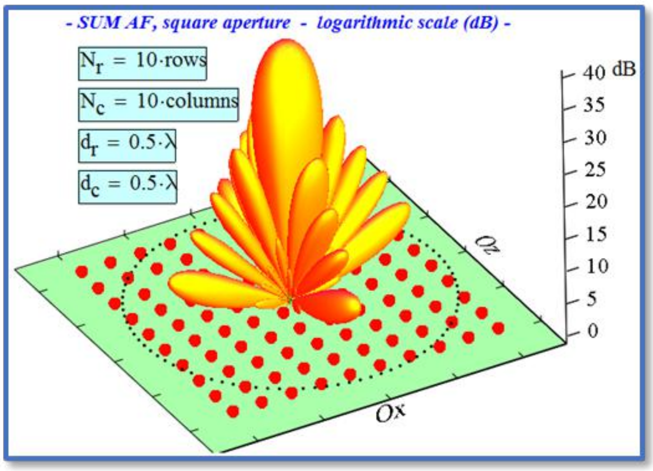


Figure 6. Absolute value of AF, in spherical coordinates, for an array of square aperture

Analyzing Fig. 6, two conclusions can be drawn:

a) the main lobe of the array factor absolute value is oriented along the axis perpendicular to the plane of the antenna array aperture. It is symmetrical, if the antenna array aperture is square or circular;

b) the side lobes of the array factor absolute value are oriented along the axes of symmetry of the antenna array.

In order to obtain a better accuracy of the angular coordinate's determination than that determined by the opening of the main lobe of the antenna pattern (*sum pattern*), the radar subsystems use the mono pulse method which consists of subtracting the patterns of two adjacent antennas / antenna arrays, obtaining a *difference pattern* (and the related difference array factor).

Fig. 7 presents an example of 3D graphical representation for overlapped sum array factor and azimuth & elevation difference array factors of the above considered antenna array.

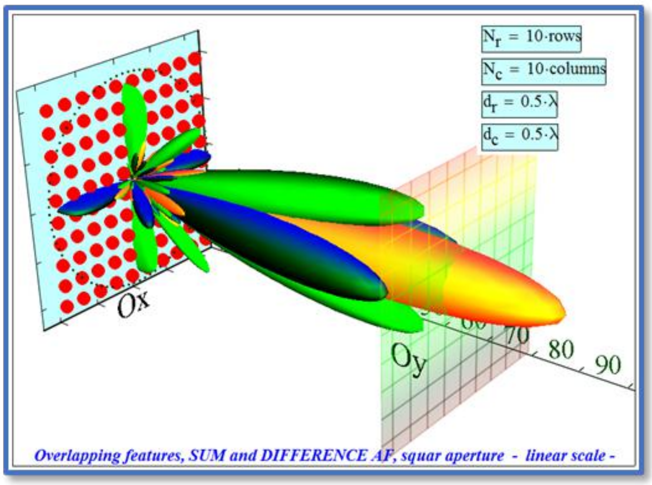


Figure 7. Absolute value of SUM AF and DIFFERENCE AF, in spherical coordinates, for arrays of square aperture

Fig. 5, 6 and 7 have been obtained by using a calculation and graphical tracing dedicated program, created using the MATHCAD software, in which the above-mentioned (2) was introduced and also, the relations of sum and difference array factors that can be found in the specific literature [8-11].

The signals emitted by the radar subsystem of a GBAD system are the main electromagnetic disturbances for other radioelectric systems in its area of action, as the level of electromagnetic energy radiated into space is very high (for example, the AN / MPQ-65 radar of the PATRIOT system, the pulse power is about 10 *kW*), and the maximum radar detection distance is 100 *km*, which implies that the electromagnetic energy transmitted at this distance has a level that cannot be neglected. The AN / MPQ-65 radar contains a circular aperture planar phased-antenna array including 5161 elements.

A simplified simulation of the electric field generated by a similar array was performed by using CST software and is presented below in Fig. 8.

The necessary input data (frequency, number of antenna elements, range) are those of the real radar system.

The attenuation of the electromagnetic waves was ignored.

As can be seen, the level of the main lobe at 100 *km* is –12.5 *dB*, which represent 5.6% from the level of the above mentioned pulse power.

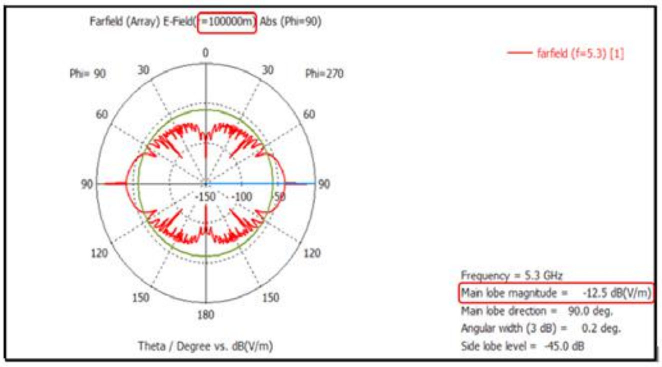


Figure 8. The electric field level radiated at 100 km by an array antenna with 5161 elements

IV. CONCLUSIONS

As shown in the previous chapter, the structure of the electromagnetic environment of a GBAD system consists of:

a) electromagnetic fields determined by the operation of electrical equipment and subassemblies in the power supply subsystem (generator set, converter, relays, contactors, transformers, etc.);

b) magnetic fields generated by the circulation of currents through conductors;

c) magnetic fields determined by the operation of electric motors in launching installations;

d) electromagnetic fields generated by the operation of electronic equipment in the launch operational control subsystem and in the radar subsystem;

e) short-term electromagnetic fields determined by the interaction between electromagnetic waves and the plasma jet emitted by the ground-to-air rocket engine;

f) electromagnetic fields generated by the communication systems in the composition of the GBAD system;

g) electromagnetic fields generated by the radar subsystem.

The categories of electromagnetic disturbances associated with these fields and their sources are as follows:

- transient, broadband-driven disturbances caused by the tripping of electrical relays, contactors and decouplers;
- stationary driven disturbances (noises), determined by the operation of electric generators / motors;
- narrowband, sinusoidal radio frequency disturbances, represented by the signals emitted by transmitters and receivers in the composition of the communications subsystems and the radar subsystem, during their operation.

The analysis of the occurrence of the electromagnetic disturbances mentioned above, as well as of their characteristics, reveals the following important conclusions:

1) these electromagnetic disturbances are neither accidental nor intentional, but are determined by the operation of the GBAD system and their occurrence cannot be avoided;

2) the level and characteristics of these disturbances indicate an important disturbing electromagnetic potential of the GBAD system, which is a major element to be taken into account in ensuring an environment characterized by electromagnetic compatibility;

3) given the purpose of using the GBAD system and the strength of the signals emitted by it, beyond that of "civilian" radio systems, improving the methods of ensuring electromagnetic compatibility between GBAD systems and other military and civilian systems is an extremely difficult task, but it is a permanent priority for producers and authorities.

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